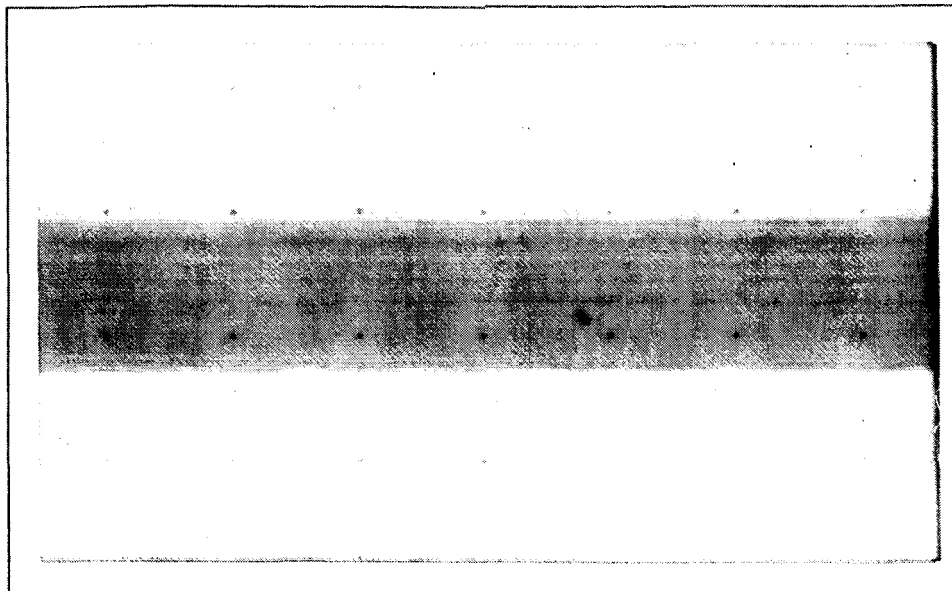


MASSACHUSETTS INSTITUTE OF TECHNOLOGY PLASMA FUSION CENTER

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CAMBRIDGE, MASSACHUSETTS 02139

(NASA-CR-181004) A PRELIMINARY STUDY OF
EXTENDED MAGNETIC FIELD STRUCTURES IN THE
IONOSPHERE Status Report (Massachusetts
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DEPARTMENT OF PHYSICS

FRANCIS BITTER NATIONAL MAGNET LABORATORY

RESEARCH LABORATORY OF ELECTRONICS

REPORT

"A Preliminary Study of Extended Magnetic
Field Structures in the Ionosphere"

James D. Sullivan, Barton G. Lane,
and Richard S. Post

June 18, 1987
NASA Contract No. NAG-5-874

In this initial study under NASA Contract No. NAG-5-874, we have identified several plasma phenomena which are to be expected around a magnet in LEO and have considered them qualitatively. The ASTROMAG cusp magnet will create an extended field whose strength drops to the ambient level over a scale length of ~ 15 m; the combined field has a complex topology with ring nulls and open and closed field lines. The entire configuration is moving through the partially ionized F-layer of the ionosphere at a speed slow compared to the local Alfven speed but fast compared to the ion sound speed; the ambient plasma crosses the extended field structure in a time short compared to the ion Larmor period, yet long relative to the electron Larmor period. Thus, electrons behave as a magnetized fluid while ions move ballistically until reflected

from the higher fields near the cusp. Since the Debye length is short compared to the field scale length, an electrostatic shock-like structure forms to equilibrate the flows and achieve quasi-neutrality. The ambient plasma will be excluded from a cavity near the magnet. We have determined the size and nature of the strong interaction region in which the magnet significantly perturbs the ambient flow by studying numerically ion orbits. Some of these results were reported at the Spring 1987 American Geophysical Union Meeting and previewed at an earlier ASTROMAG team meeting. A copy of the viewgraphs used for a talk at the IEEE Plasma Physics Meeting are attached for reference. These viewgraphs summarize the results of this initial study in greater detail.

**Physics of Man-Made Extended
Magnetic Structures
in Low Earth Orbit**

**J. D. Sullivan, B. G. Lane,
J. H. Irby, R. S. Post,
MIT Plasma Fusion Center**

Presented at IEEE Meeting, June 1-3, 1987, Arlington, Virginia,
by James D. Sullivan on June 2.

Physics of Man-Made Extended Magnetic
Structures in Low Earth Orbit*

J.D. Sullivan, B.G. Lane, J.H. Irby, R.S. Post,
Plasma Fusion Center M.I.T., Cambridge, MA 02139

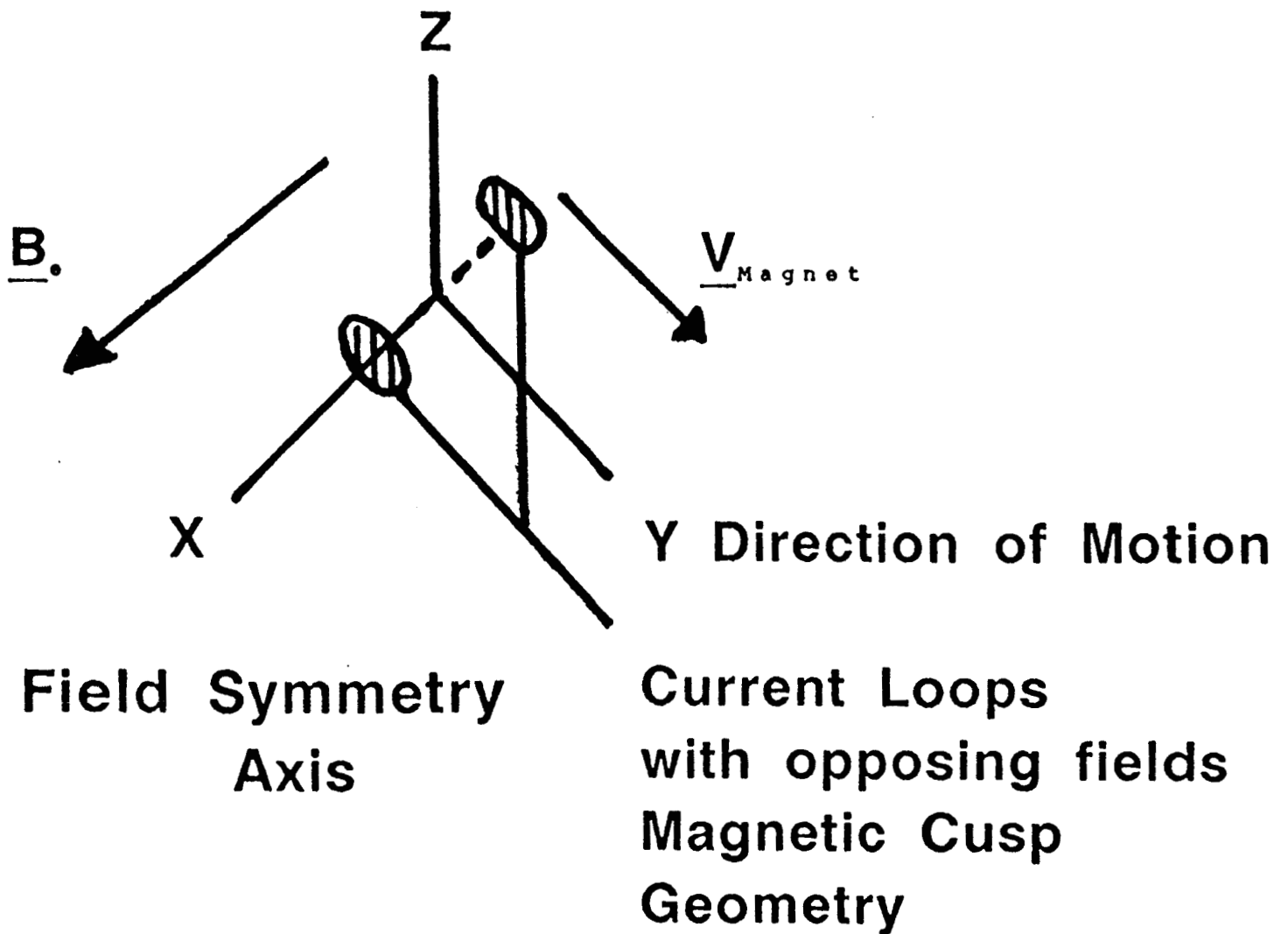
Recently there have been proposals to place high field magnets aboard the Space Station. The introduction of such an extended magnetic field structure into low earth orbit raises a number of interesting plasma physics issues. For example, the ASTROMAG magnet would create an extended magnet field whose strength drops to the ambient level of .3 G over a scale length of approximately 10 m. The combined field from the cusp magnet and the earth produces a complex extended configuration with ring nulls which separate open from closed field lines. This configuration will move through the ambient $1 \times 10^5 \text{ cm}^{-3}$ plasma at a velocity of approximately 7 km/sec, a velocity slow compared to the Alfvén speed, but fast compared to ion sound speed. The ambient plasma crosses the field structure in a time short compared to an ion Larmor period in the ambient field, but long compared to an electron Larmor period. Thus, electrons behave as a magnetized fluid while ions move ballistically until they approach and reflect from the higher fields near the cusp. Since the ambient plasma Debye length is short compared to the field scale length, an electrostatic shock structure forms to equilibrate the flows in order to achieve quasi-neutrality. We conjecture based on previous laboratory experiments that the ambient plasma will be excluded from a cavity surrounding the magnet. The gross morphology of the flow is similar to a sphere moving supersonically through a fluid, although the shock structure is complicated by the magnetic field. We have studied numerically the ion and electron trajectories in the combined magnetic fields of the Astromag cusp magnet and the ambient earth field. Ion orbits are used to estimate the size and nature of the strong interaction region in which the magnet significantly perturbs the ambient flow. Electron orbits are examined to estimate the energy gain due to the motional potential drop across the structure of $\sim 8 \text{ V}$. Instabilities and the possibility of large scale, electrostatic convective cells such as seen in laboratory plasmas will be considered and the interactions between energetic ions and electrons and the enhanced neutral environment of the Space Station will be considered.

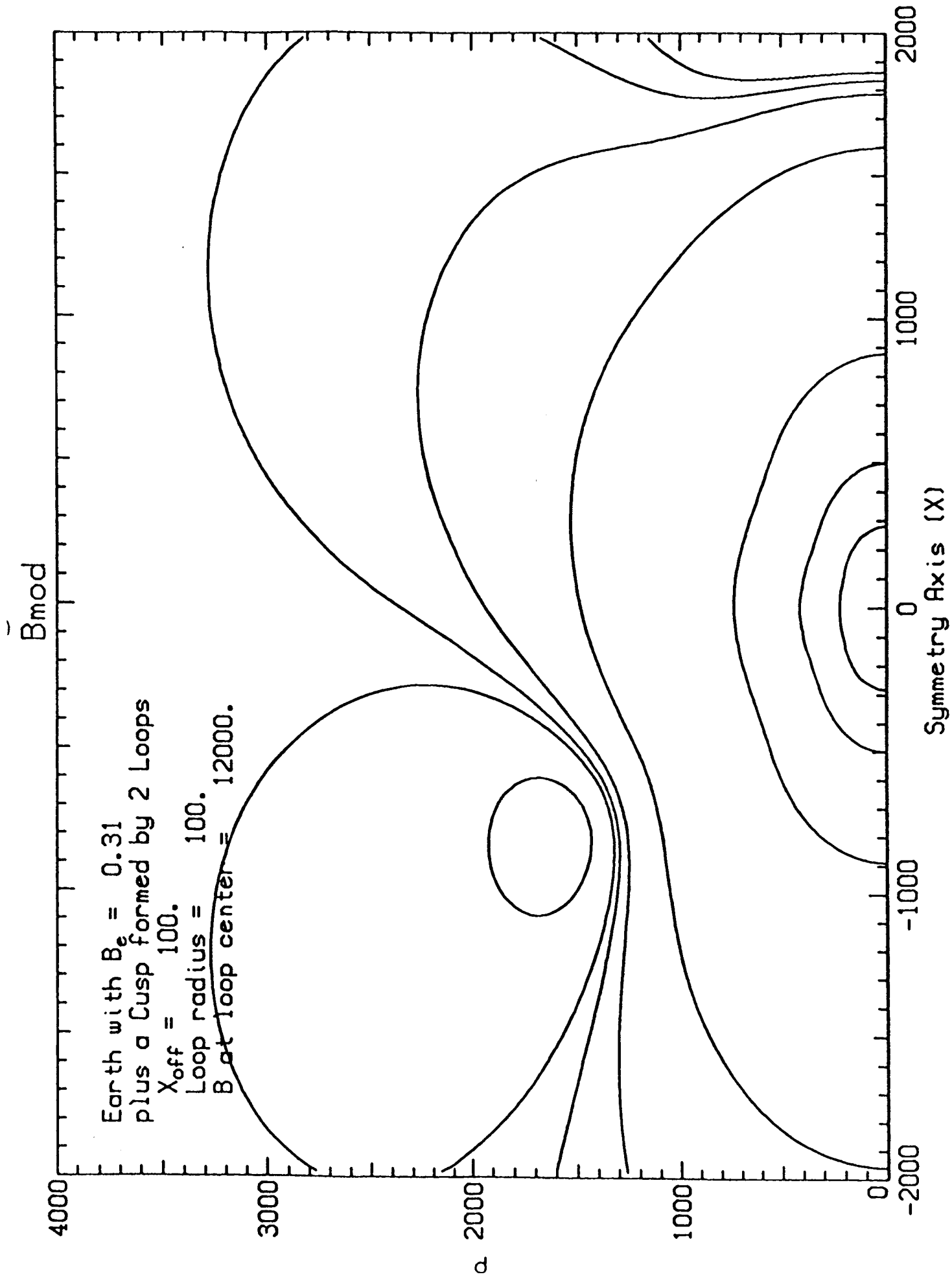
*Supported in part by NASA grant #NAG-5-874

EXTENDED MAGNETIC FIELD STRUCTURES IN LOW EARTH ORBIT

- Implications for experiments utilizing magnetic fields (ASTROMAG)
- Unique opportunity to study rich set of basic plasma physics issues
 - Novel parameter regimes
 - Complex magnetic geometry with adjustable scale lengths
 - Controlled, interactive, well diagnosed modification of local plasma environment

GEOMETRY





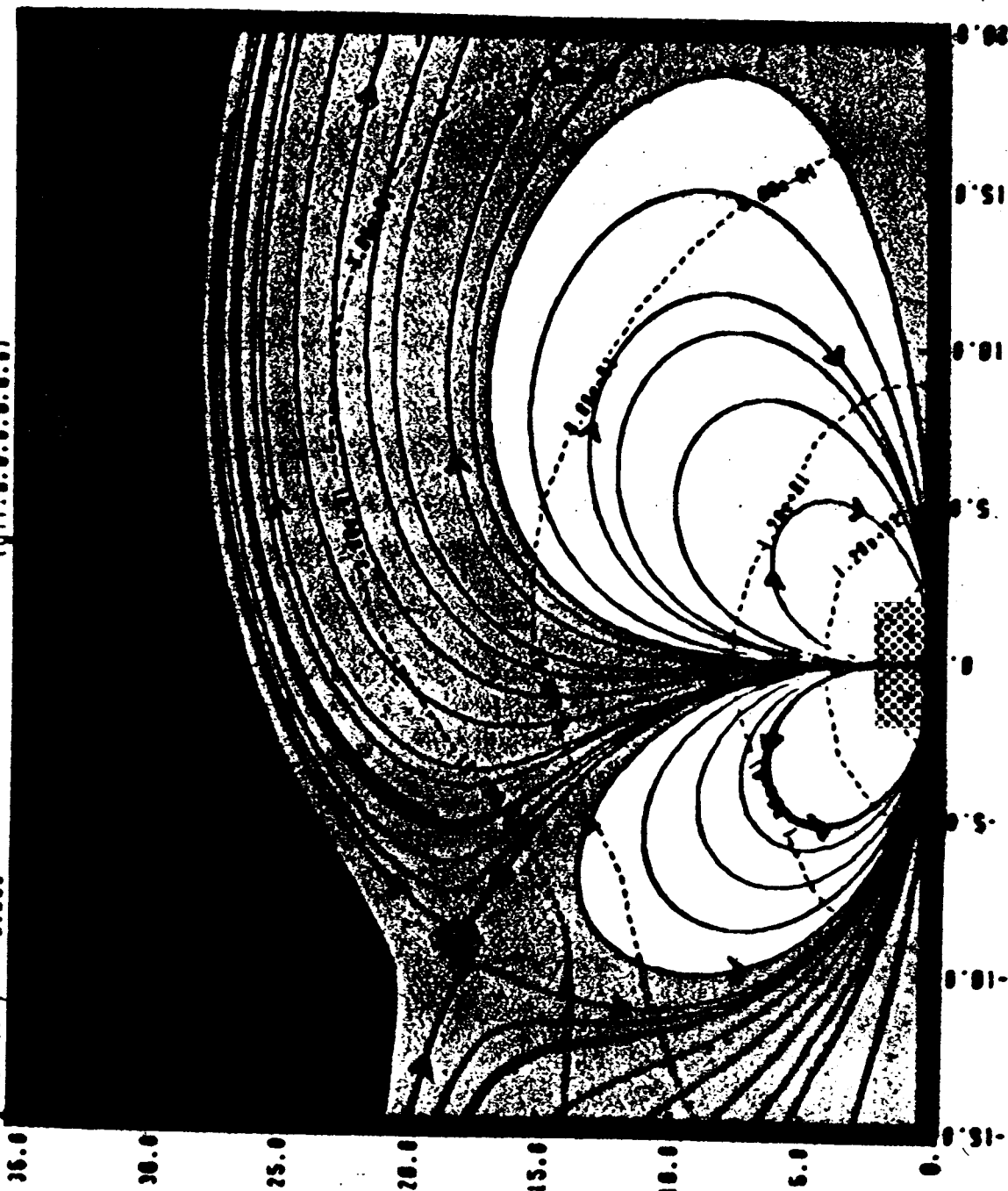
MORPHOLOGY OF MAGNETIC STRUCTURE

Example: Cusp magnet immersed in ambient field

- Topology of field structure
 - Closed field line regions
 - Open field line regions
 - Ring and point nulls
- Vacuum fields only marginally perturbed by ram pressure
- Scale size adjustable by varying magnet field strength

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ASTRONAG cusp with Earth's field
Grid 1. y. 0.000
12:24:00 e 10/22/86
(q11:0.0.0.0.0.0)

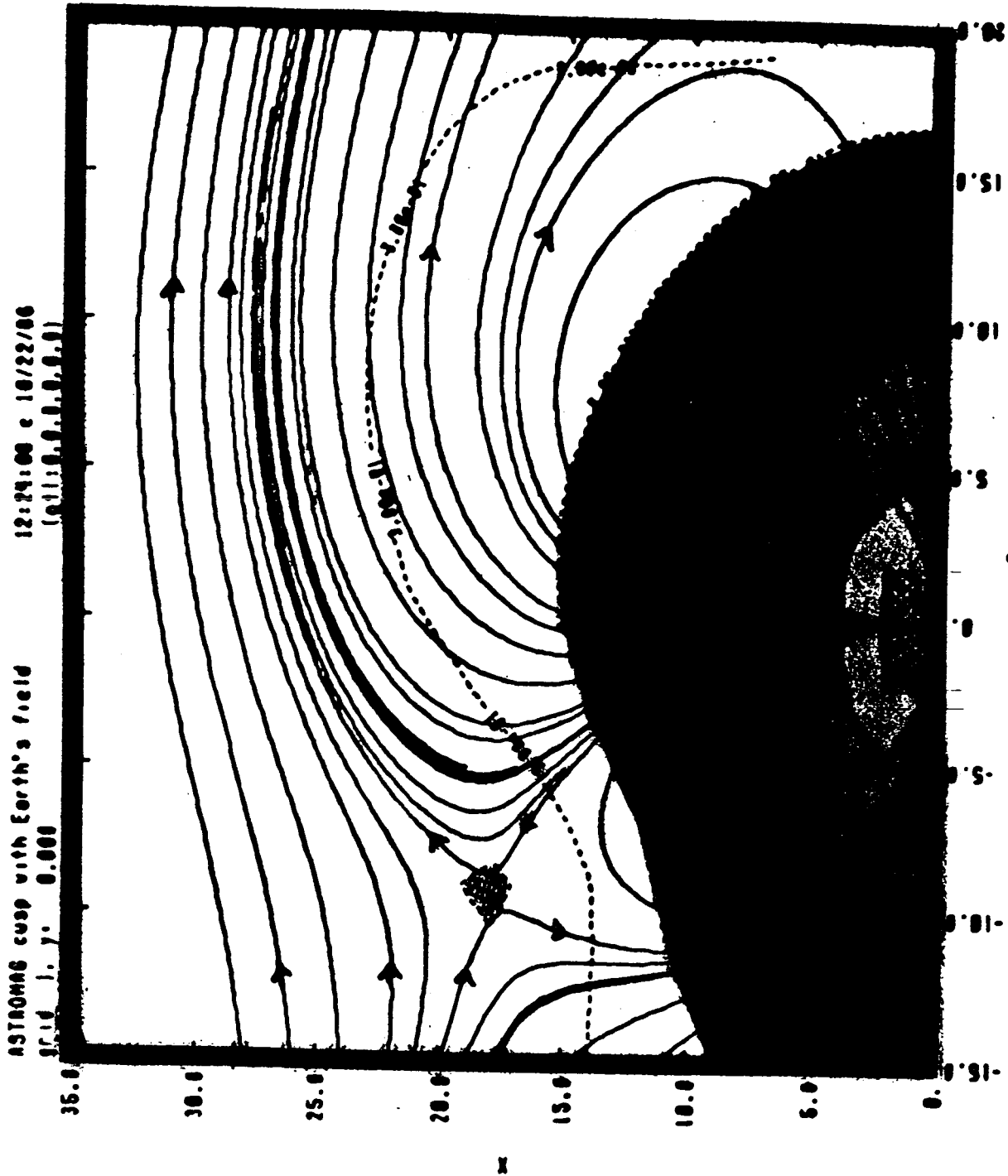


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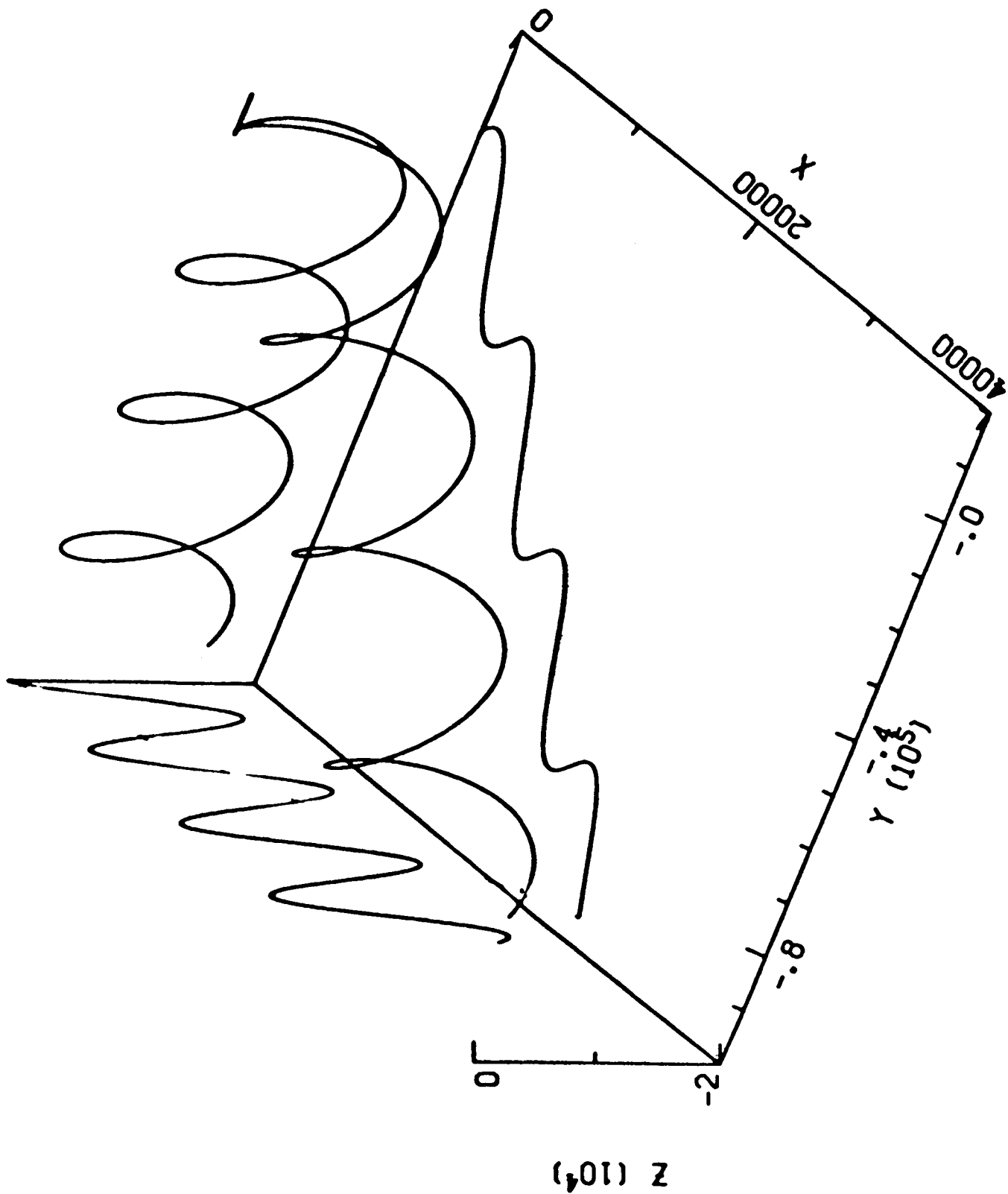
(Specialize to frame in which magnet is at rest)

- Electrons - Strongly magnetized
 - $\mathbf{E} \times \mathbf{B}$ drifts across \mathbf{B}
 - Rapid thermal streaming along \mathbf{B}
- Ions
 - Region I $\rho_i > L_B \approx 15\text{m}$ - Ions "unmagnetized"
 - Region II $15\text{m} > \rho_i > .5\text{m}$ - Transition Region, complex ion orbits
 - Region III $\rho_i < .5\text{m}$ - Ions Strongly Magnetized

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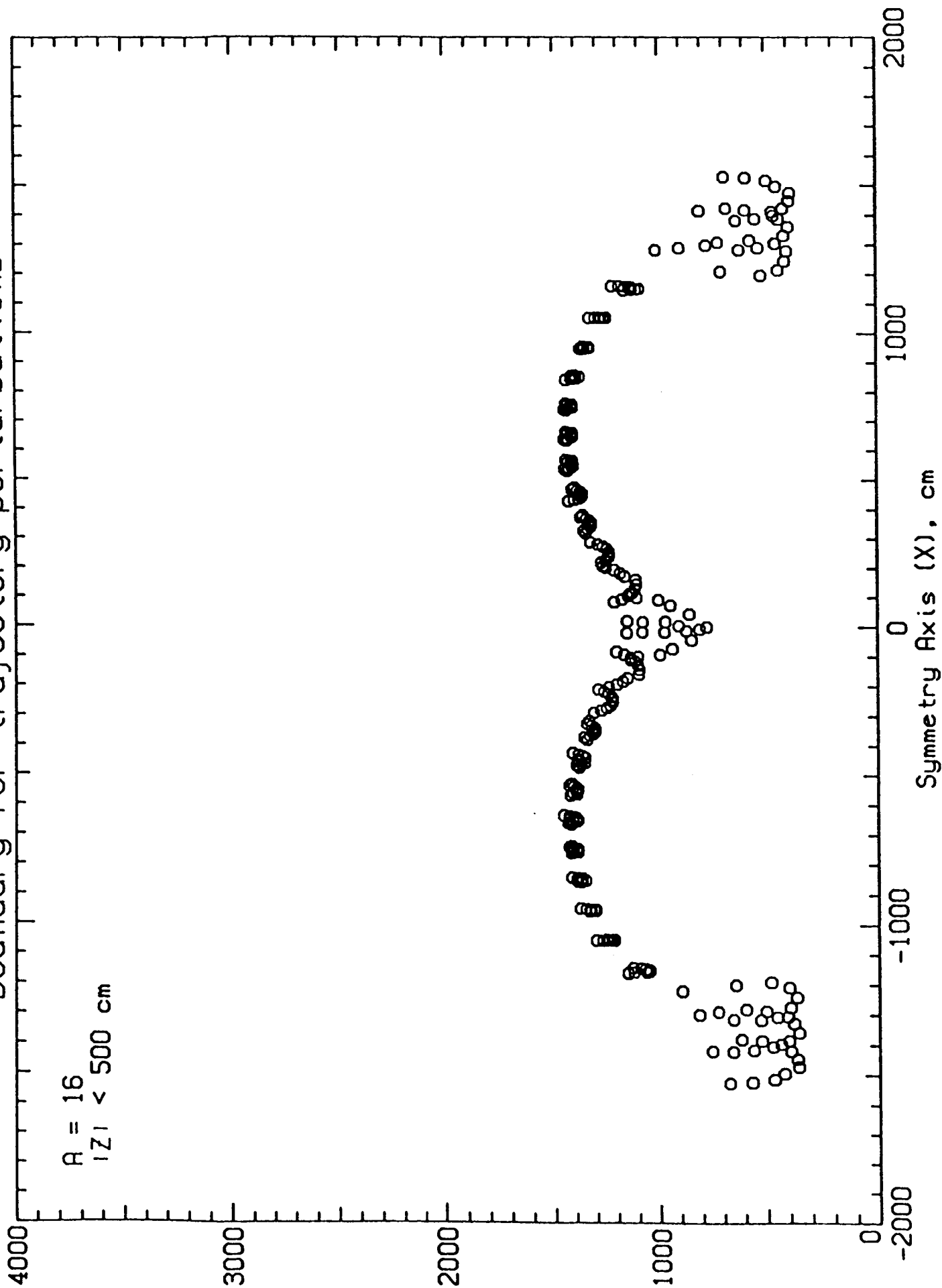
A = 16.



Orthogonal Projection: theta = 45.0, phi = 30.0

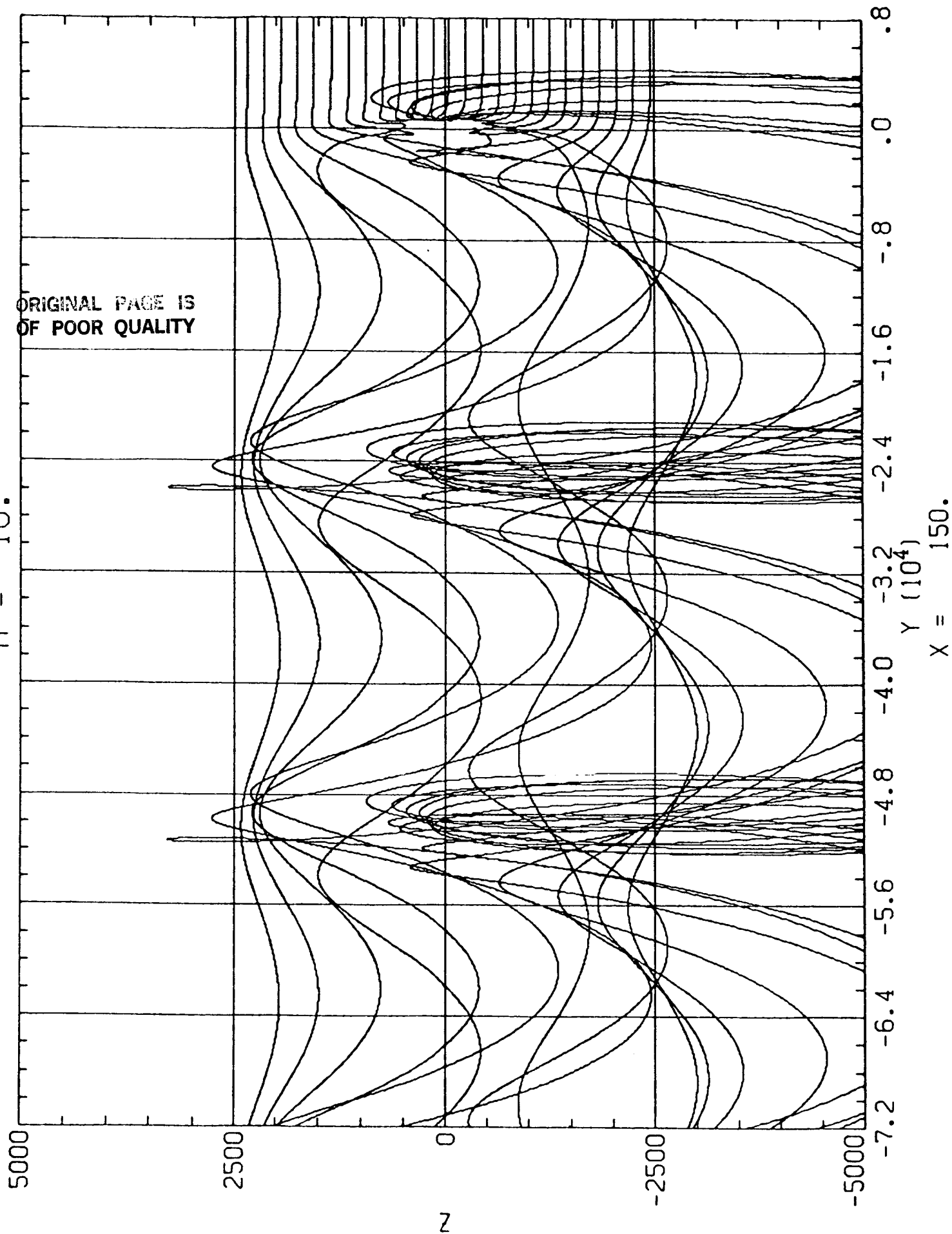
Boundary for trajectory perturbations

$A = 16$
 $|Z| < 500 \text{ cm}$



A = 16.

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GLOBAL POTENTIAL STRUCTURES

- Extended (- 20-30m diameter) electrostatic shock structure in transition region to achieve quasi-neutrality (difficult to duplicate in laboratory)
- Field aligned potential structures develop to equilibrate electron and ion flow to magnet casing
- Potentials - 8V
- Large wake region - turbulent cascade of long wavelength electrostatic modes
- Motional potential drop across structure -10V
- Converging open field lines amplify motional field to 1V/cm at magnet case
- Repeatable measurements possible because structure is stationary

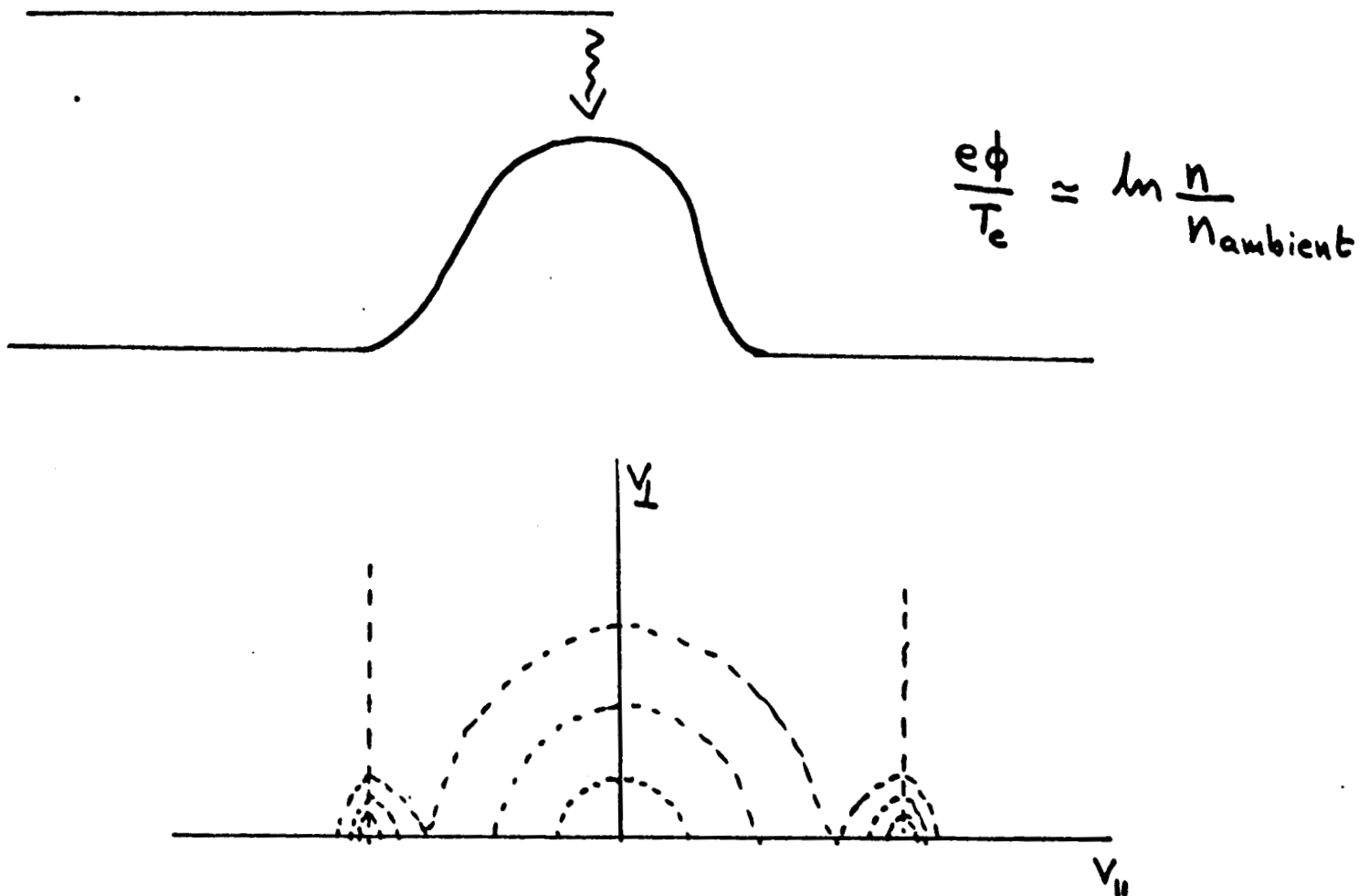
SUPER-SONIC FLOW OF AMBIENT PLASMA AROUND MAGNETIC OBSTACLE

- **Extended (10 - 20 m) electrostatic shock structure forms to achieve quasi-neutrality**
- **Field aligned potential structures develop to equilibrate electron and ion flows to magnet casing on single ended open field lines**
- **Motional potential drop ~ 10 V**
- **Converging open field lines carry motional electric field to 1 V/cm at magnet case**
- **Large wake region**

CREATION OF CONFINED PLASMA ON CLOSED FIELD LINES

- High density neutral environment due to outgas and thruster firing (up to $1e-4$ Torr)
- Electron heating channels
 - ion two stream instability - (may be cause of enhanced wake electron temperatures on shuttle)
 - motional potential drop partly along field lines
 - Kelvin-Helmholtz instabilities at interfaces of confined and flowing plasmas
- Enhanced electron energy confinement due to mirror ratio on closed field lines ($R \sim 150$)
- All the ingredients are present for creation of high density confined plasma

ELECTRON ENERGY LOSS CHANNELS IN UNCONFINED PLASMA



Trapped electrons lose energy by

- scattering out of potential well
- cooling on passing ambient electrons

Characteristic times:

Ion loss time:

$$\frac{L}{c_s}, \quad \frac{L}{u_{sc}}$$

$$c_s \equiv \left(\frac{T_e}{m_i} \right)^{1/2}$$

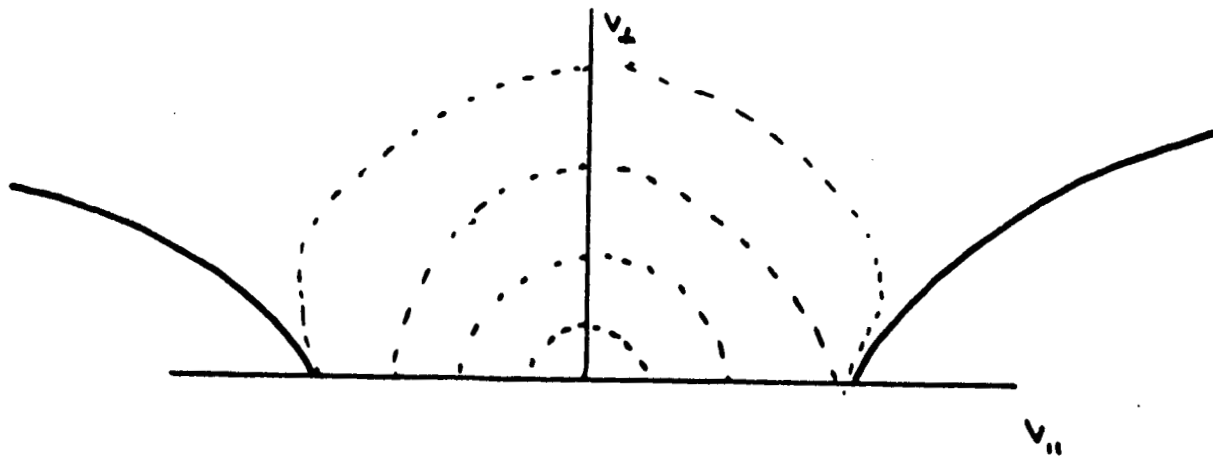
ELECTRON ENERGY LOSS CHANNELS IN CONFINED PLASMA

Electrons lose energy by

- scattering into loss cone
- excitation and ionization of neutrals

Characteristic times:

$$\frac{1}{R} \frac{L_{\parallel}}{c_s}, \quad \frac{1}{R} \frac{L_{\perp}}{u_{sc}}$$



WHY STUDY MAN MADE MAGNETIC FIELD STRUCTURES IN LOW EARTH ORBIT ?

- Rich set of basic plasma physics phenomena
 - super-sonic, sub-Alfvenic flows
 - turbulent drift wave spectra in wake
- Implications for space based experiments utilizing magnetic fields (ASTROMAG)
- Relevant to naturally occurring sub-Alfvenic, super-sonic flows in 3-D geometries
- Implications for space craft charging